AD-A074 406 IIT RESEARCH INST CHICAGO IL F/G 20/1
ULTRASONIC SURFACE WAVE TRANSDUCTION TECHNIQUES.(U)
1973 R J SERAFIN
UNCLASSIFIED IITRI-CRTN-100 NL

1 OF 1
AD
A074406

END
DATE
FILMED
11-79
DDC

MOST Project -4

OOVI LIBRARY COPY

LEVEL II

AD A074406

(14) IITRI-CRTN-100

(9) C & R Technical Note No. 100

Project E1059

(6) Ultrasonic Surface Wave Transduction Techniques

(10) R. J. Serafin

(11) 1973

(12) 23p.

DDC FILE COPY

DDC
RECEIVED
SEP 28 1979
A

Accession For	
NTIS GRA&I	☑
DDC TAB	☐
Unannounced	☐
Justification	
By Letter on file	
Distribution/	
Availability Codes	
Dist.	Avail and/or special
A	

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

IIT RESEARCH INSTITUTE

175350

C & R Technical Note No. 100

Ultrasonic Surface Wave
Transduction Techniques

I. INTRODUCTION

The work conducted on Project E1059 has been an extension of that begun on Projects E1014, E1022 and continued under Project E6044. Primarily, this work has been concerned with the development of techniques for tapping ultrasonic delay lines. These techniques utilize thin deposited conducting, piezoelectric, and piezoresistive films on a Pyrex glass substrate. The mode of propagation has been the surface wave which provides maximum energy on the surface and is free from dispersion and reflections. Details of the techniques developed may be found in IITRI Technical Note No. 02-3, entitled "Thin Film Multi-Tap Delay Line" authored by R. J. Serafin and A. P. van den Heuvel.

Effort on this program has concerned itself with investigation of piezoelectric taps employing a vertical geometry. A thin film surface wave generator was designed and successfully deposited. During the program a paper entitled "Measurement of Strain and Velocity of Ultrasonic Surface Waves" was submitted and accepted for publication in the October 1967 issue of The Review of Scientific Instruments. In addition, a paper entitled "Thin Film Surface Wave Transducers" was presented at the IEEE Symposium on Sonics and Ultrasonics and will be submitted for publication in the IEEE Transactions. Authors of the above papers are R. J. Serafin, D. Fryberger, and M. Epstein for the former and R. J. Serafin and A. P. van den Heuvel for the

latter. A patent application has been initiated under No. 6-23-674, "Tapping Techniques for Nonmagnetic Delay Lines."

II. ANALYSIS

A. Strain Calculation

The vertical geometry tap takes the form of a thin piezoelectric film sandwiched between a common lower electrode and narrow upper electrodes which may be placed at will along the propagation path. For piezoelectric films deposited normally to the substrate, the piezoelectric effect should also be primarily normal to the surface and hence the taps should respond only to normal strain. With surface wave propagation such a strain exists as a consequence of its characteristic decay with depth into the surface. The longitudinal and transverse components of displacement may be written[1]

$$u_x(x,y,t) = A\, f_x(y)\, \sin(\omega t - kx) \quad (1)$$

$$u_y(x,y,t) = -A\, f_y(y)\, \cos(\omega t - kx) \quad (2)$$

where u_x is the particle displacement wave function in the direction of wave propagation (the x direction), u_y is the particle displacement transverse to the direction of propagation, f_x and f_y are functions describing the behavior with depth, y, and are functions of depth only, ω is the angular frequency, $k = 2\pi/\lambda$, and A is a constant. Both u_x and u_y are assumed constant in a third spacial dimension, z, and thus Eqs. (1) and (2) represent a surface wave equivalent of plane wave propagation.

[1] E. G. Cook and H. E. Van Valkenbrug, ASTM Bulletin, Vol. 198, May 1954.

The various strains that exist may be obtained by differentiating Eqs. (1) and (2) with respect to the spatial variables x and y. In particular, the strain to which the taps will respond is the normal strain S_{yy} given by

$$S_{yy} = \frac{\partial u_y}{\partial y} = -A\ f'_y(y)\cos(\omega t - kx). \tag{3}$$

Since the taps reside on the surface we are interested only in the values of S_{yy} for $y = 0$. Thus we may write

$$S_{yy}(x,0,t) = -A\ f'_y(0)\cos(\omega t - kx). \tag{4}$$

The particle velocity is given by

$$v_y = \frac{\partial u_y}{\partial t} = A\,\omega\, f_y(y)\sin(\omega t - kx). \tag{5}$$

which again at the surface becomes

$$v_y(x,0,t) = A\,\omega\, f_y(0)\sin(\omega t - kx). \tag{6}$$

If we concern outselves only with amplitude, we may write

$$|S_{yy}| = |v_y|\ \omega\left|\frac{f'_y(0)}{f_y(0)}\right| \tag{7}$$

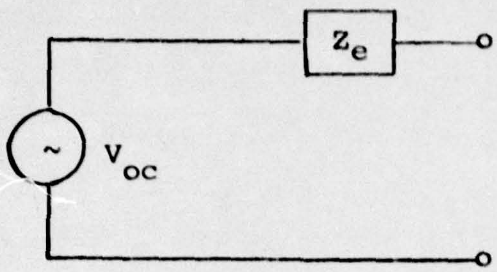
Since v_y can be measured, utilizing the kinetomagnetic technique, ω is known, and f_y and f'_y are functions of the substrate and also are known[1], the magnitude of the normal strain S_{yy} can be easily determined.

With the vertical geometry the temptation is strong to consider the tap to operate simply as a conventional piezoelectric

---

[1] Ibid.

transducer well below resonance.* For this situation a simple equivalent circuit as shown below may be devised.[1]



In this simple circuit Z_e is the electrical impedance of the transducer and V_{oc}, the open circuit voltage, is given by

$$V_{oc} = \frac{F \alpha Z_e}{Z_m + \alpha^2 Z_e} \qquad (8)$$

where Z_m is the mechanical impedance of the transducer, F is the mechanical driving force, and α is an electromechanical coefficient given by

$$\alpha = \frac{e_{hj} A}{t} \qquad (9)$$

where e_{hj} is a piezoelectric stress constant, A is the transducer area and t is its thickness (in this case the thickness of the film).

In piezoelectric materials, e_{hj} relates the charge developed per unit area (polarization) to an applied strain by the expression

$$P_h = e_{hj} S_j \qquad (10)$$

---

*Since the taps are of the order of 1.0μ thick and a wavelength at 10 MHz is of the order of .3 mm, this condition is satisfied.

[1] T.F. Heuter and R.H. Bolt, Sonics, John Wiley & Sons, 1962.

where P_h is the polarization in the h direction due to a strain in the j direction. From Eq. (10) we see that e_{hj} is actually an element of a tensor and for completeness shear as well as longitudinal strains should be included. Since there are six possible components of strain (3 shear and 3 longitudinal) and three components of polarization there are required 18 (6 for each polarization component) piezoelectric stress constants to characterize the peizoelectric properties of a material. In practice, it is usually sufficiently accurate to consider only the effect for $h = j$ where the polarization and strain are in the same direction. In our case this direction is normal to the surface. Relating Eq. (10) to the notation used earlier we have

$$P_y = e_{yy} S_{yy} \tag{11}$$

Glancing at Eq. (8) it is important to note that the open circuit voltage is dependent upon the value of the electrical impedance Z_e of the transducer. This should be expected since the piezoelectric stress constant relates polarization or charge to the strain. The voltage developed, however, will be determined by the charge and the capacitance of the tap.

It will be useful now to consider in more detail Eq. (8). We can begin by examining first Z_e which is simply a capacitance in parallel with a resistance. The capacitance, C_o, is given by

$$C_o = \frac{\varepsilon A}{t} \tag{12}$$

where ε is the product of the relative dielectric constant of the piezoelectric and the permittivity of free space. The resistance of the tap is given by

$$R = \frac{\rho t}{A} \tag{13}$$

where ρ is the resistivity of the piezoelectric. The impedance Z_e is given by the parallel combination of C_o and R as

$$Z_e = \frac{R}{1+j\omega RC_o} \, . \tag{14}$$

Substitution of Eqs. (12) and (13) into (14) yields

$$Z_e = \frac{\rho t/A}{j\omega\varepsilon\rho+1} \, . \tag{15}$$

Now, if $\omega\rho\varepsilon >> 1$, Eq. (15) becomes

$$Z_e \approx \frac{t}{j\omega\varepsilon A} = \frac{1}{j\omega C_o} \tag{16}$$

which states that the electric impedance of the tap is primarily a capacitance. This can be accomplished either with high frequency operation, large dielectric constants, or high resistivity. In most bulk peizoelectric materials, the resistivity is very high and Eq. (16) is valid. However, the deposited thin film transducer may not have a resistivity high enough in order to validate Eq. (16). For example, if we desire $\omega\rho\varepsilon >> 1$, we require

$$\rho >> \frac{1}{\omega\varepsilon} \, . \tag{17}$$

For operation at 10 MHz and a relative dielectric constant of five, Eq. (17) becomes

$$\rho >> \frac{1}{2\pi \times 10^7 \times \frac{5}{36\pi} \times 10^{-9}} = 36 \times 10 = 360\ \Omega m = 36000\ \Omega cm \tag{18}$$

Thus for operation at 10 MHz, Eq. (16) may not be used unless the films exhibit resistivities of the order of $10^5\ \Omega$cm or greater.

Equation (18) may further be modified by noting that

$$\frac{F}{A} = c_{yy} S_{yy} \tag{19}$$

and

$$Z_m \approx \frac{c_{yy} A}{t} \frac{1}{j\omega} \tag{20}$$

Equation (19) is a statement of Hooke's law where c_{yy} is the stiffness constant.[1] Equation (20) is valid well below resonance where the transducer is stiffness controlled.[1] Substitution of Eqs. (16), (19), and (20) into (8) yields

$$V_{oc} = \frac{c_{yy} e_{yy} S_{yy} t}{\varepsilon \left(c_{yy} + \frac{e_{yy}^2}{\varepsilon} \right)} . \tag{21}$$

The above agrees well with intiution, i.e., the output voltage is proportional to the strain, the thickness of the film, and basic constants of the material.

B. Results and Conclusions

The validity of Eq. (21) and the assumed equivalent circuit of the taps has not been established experimentally. While it appears simple to measure the voltage, film thickness and strain, a number of factors militate against drawing simple conclusions from these measurements. First, the CdSe films, deposited at room temperature, have exhibited resistivities no greater than $10^4\ \Omega$ cm. Thus, at 10 MHz, the resistance of the film cannot be neglected in the analysis. Secondly, the practical

[1] Ibid.

problem of depositing successive films, even on the same substrate, with identical characteristics is by no means trivial. It is also difficult to deposit an electrode structure which makes good ohmic contact to the piezoelectric, hence measurement of the film resistivity is difficult. Lastly, there is reason to believe that the films, as they are deposited, do not grow homogeneously; in particular, strong evidence exists that the thinner films (< 500 Å) may not be piezoelectric at all.

One conclusion that can be drawn from the results obtained is that the vertical geometry taps are much more sensitive than those which use a planar geometry. Secondly, the tap output is definitely thickness dependent, however, the exact functional form of this dependence cannot be determined from the data collected to date. Another result, which agrees qualitatively with theory, has been that those films with the lowest resistivity have proved to be the poorest sensors. In comparing the sensitivities of many of the films deposited with results obtained by Clevite Corporation[1], it is clear that an order of magnitude or more sensitivity should be available with better films of high resistivity.

Attempts to deposit a thin film surface wave generator utilizing periodic electrode structures have been successful on a single occasion. In this case the piezoelectric was deposited

---

[1] T.R. Sliker, "Ferromagnetic, Ferroelectric, and Acoustic Devices," First Quarterly Report, Contract No. DA 28-043 AMC-01359(E), September 1965.

so as to provide a component of the c-axis parallel to the surface. Over this was deposited an interleaved comb electrode, the distance between electrodes being 1/2 wavelength at 10 MHz. This transducer was used to successfully generate a 10 MHz surface wave. However, the power in the wave was much lower (orders of magnitude) than what can be obtained with the Lucite wedge transducers. Nevertheless, these results have demonstrated that the thin film transducer is feasible. With better films and at higher frequencies such devices could indeed prove practical. Vertical geometry thin film transducers have not proved to be effective generators. This may well be due to the electrode structure employed and must be considered in more detail. An entirely different scheme for surface wave generation would employ thermal expansion in deposited electrodes to generate the strain pulses. Preliminary calculations have indicated that very large strains can be obtained in this fashion. However, elaborate heat sinking techniques might be required for high frequency operation.

It appears that the largest hurdle to be cleared is obtaining high frequency operation (up to 1 kHz or more) by developing effective surface wave generators. Deposited generators and thermal expansion have been suggested as possibilities. However, another possibility might employ incident shear waves in a CdS wedge. Acoustic amplification could be used to increase the incident energy. Also, the driving shear transducer could be deposited CdS on the wedge thus giving an excellent acoustic impedance match. Silicon or sapphire substrates might also be

employed. These materials exhibit high acoustic velocities which might permit the use of incident compression waves in CdS wedge transducers.

OOVL LIBRARY COPY

Good

00005

What Are Elastic Surface Waves?

Elastic Surface Waves are sonic waves which propagate on the surfaces of solids.

The amplitude of the disturbance decays exponentially with depth into the surface: most of the energy is confined to a layer a wavelength thick near the surface.

These waves are known as Rayleigh waves after Lord Rayleigh who described them in 1885.

The velocity of Rayleigh waves is independent of frequency, for a free surface, and is approximately 10^5 times slower than E-M waves.

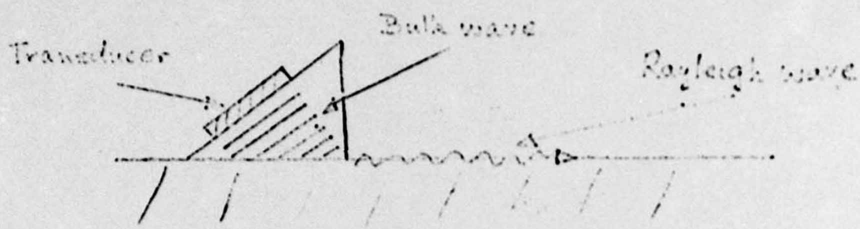
The velocity of Rayleigh waves may be made to vary with frequency (i.e., become dispersive) by the presence of a superficial layer on the propagating surface.

The attenuation of Rayleigh waves is quantitatively similar to that for other forms of sonic waves.

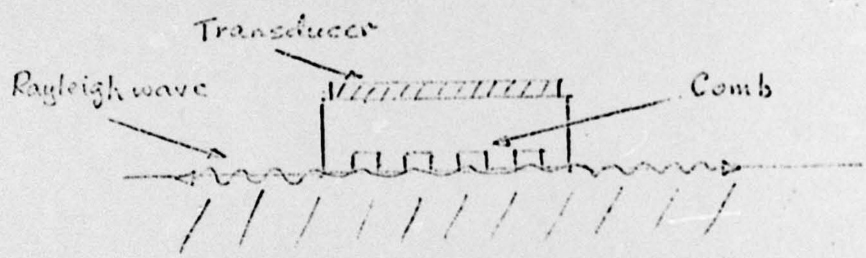
How Are They Generated?

Rayleigh waves may be generated in several ways.

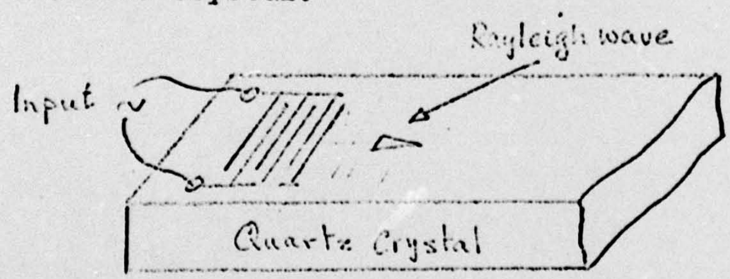
1. By means of mode conversion from a bulk wave using a wedge.



2. By means of a multi-toothed comb.



3. By means of an interdigitated electrode array on a piezo-electric crystal.



Rayleigh waves with frequencies as high as 1 GHz have been generated by method (3).

Frequencies higher than 10 GHz should be possible.

What Happens in the Presence of a Superficial Layer?

In the presence of a thin layer, the velocity of Rayleigh waves becomes a function of frequency -- this is known as dispersion.

The magnitude of the dispersion depends upon the thickness and nature of the superficial layer, and may be made positive or negative by selection of materials.

Thus, a dispersion characteristic of almost any desired form may be made by selection of layer thickness and material -- and may be varied from point to point along the surface.

What Advantage Have Rayleigh Waves Over Bulk Waves for Delay Lines?

Since Rayleigh waves are confined to the surface, they may be easily tapped at a large number of positions to make coded filters of many types.

Pulse compression delay lines are readily constructed using the ability to control the dispersive characteristics.

Spurious reflections and multi-path propagation are easily suppressed by absorbing layers.

The generators and taps are readily fabricated by thin film deposition techniques.

Several sets of taps may be made on one delay line -- one for each doppler channel.

A surface wave delay line can have a common substrate with other circuit elements or integrated circuits.

Can Rayleigh Waves be Amplified?

Rayleigh waves can be amplified in at least two ways:

1. By propagation on a single crystal of a piezoelectric semiconductor such as CdS in the presence of a drift field, gain is obtained in a manner completely analogous to a microwave travelling wave tube.

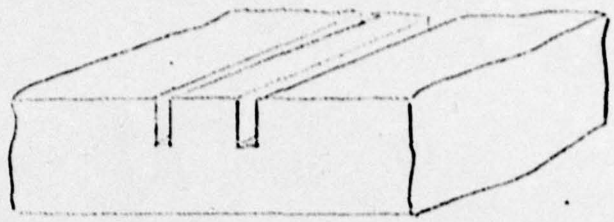
2. By propagation on a piezoelectric substrate on which a semiconductor is placed. A drift field is applied across the semiconductor.

Net gains in excess of 6 db have been attained in this way for devices less than 1 cm in length.

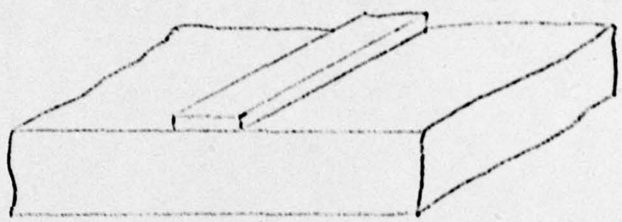
Can Rayleigh Waves be Guided Around Corners?

Rayleigh waves may be guided along curved paths in three ways.

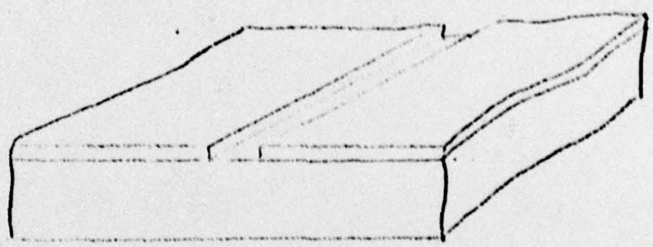
1. By means of slots cut into the surface.



2. By means of a narrow strip deposited on the surface.



3. By means of a narrow slot in a superficial layer.



The function of these guides for Rayleigh waves is analogous to a dielectric waveguide for electromagnetic waves.

What Other Electronic Functions Can Rayleigh Waves Perform?

In addition to amplification and guiding, it appears that Rayleigh waves can be made to perform all the normal distributed circuit functions, such as:

- Couplers
- Isolators
- Phase Shifters
- Mixers
- Switches
- Resonators
- Circulators
- Attenuators

By combining all these functions, complete microwave circuits can be constructed.

How Big Would Such a Circuit Be?

Since the velocity of Rayleigh waves is 10^5 times less than E-M waves, the wavelengths are also 10^5 times smaller.

	0.1 GHz	1.0 GHz	10 GHz
E-M wave	300 cm	30 cm	3 cm
Rayleigh wave	0.003 cm	3 μm	0.3 μm

An approximately similar shrinkage factor may be anticipated for the circuit elements at these frequencies by employing Rayleigh waves.

Are There Other Advantages Than Small Size?

In addition to being small, microwave circuits using Rayleigh waves:

1. Use common substrate with delay lines.
2. Have low power requirements.
3. Are economic to manufacture.
4. Can be integrated with conventional integrated circuitry.
5. Use same technology as existing integrated circuits.
6. Can be batch fabricated.
7. Are more resistant to hostile environments.
8. Are more resistant to E.M.P.
9. Emit no compromising radiation.
10. Are inherently rugged.
11. Are lightweight.
12. Use basically cheap materials.

What about Attenuation?

The attenuation of Rayleigh waves is approximately the same as that for bulk acoustic waves in the same medium.

For bulk waves in:	The attenuation is:
Lithium Niobate	0.2 db/cm at 1 GHz.
Crystalline Quartz	5.7 db/cm at 0.9 GHz.
Fused Quartz	19.3 db/cm at 1 GHz.

However, these figures are for delay line use.

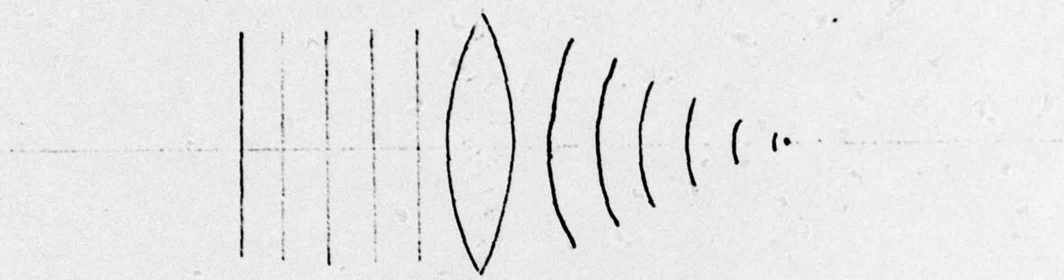
For circuit use, we need to know the loss per wavelength.

Lithium Niobate:	7.5×10^{-5} db/λ at 1 GHz.
Fused Quartz:	6.6×10^{-3} db/λ at 1 GHz.
Copper waveguide or coaxial cable	5×10^{-2} db/λ at 1 GHz.

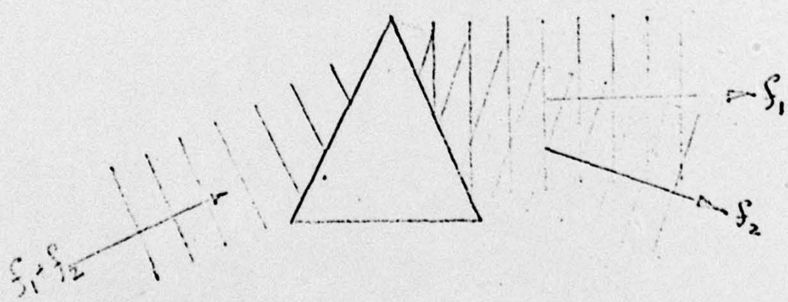
What Non-Electronic Functions Can They Perform?

By using shaped deposits on a surface, Rayleigh waves may be:

1. Focussed:



2. Refracted:



These elements could be combined for a spectral analyzer or other optical transformation functions.

What Are The Problems?

Before Rayleigh waves may be employed at microwave frequencies, further research is needed to:

1. Fabricate and evaluate devices.
2. Develop techniques for high resolution patterns.
3. Improve insertion loss and bandwidth of transducers.
4. Fabricate and evaluate guiding structures at microwave frequencies.
5. Improve theoretical understanding and prediction of waves in partially layered media.
6. Evaluate new device concepts.

To perform research in this subject, contributions from the following disciplines is necessary:

1. Microwave engineering.
2. Microelectronics.
3. Solid state physics.
4. Ultrasonics.
5. Thin film technology.
6. Crystallography.
7. Theoretical physics.
8. Materials.

(9. Conventional hard work.)